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# Antiproton Stacking and Cooling

Dave McGinnis  
Director's Review  
July 1, 2003

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# Outline

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- Parameter Goals
- Strategy
- Antiproton Stacking Process
- Projects
- Project Strategy
- Key Parameters
- Cost and Schedule

# Parameter Goals

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## ■ Goals

- Average Stacking Rate  $40 \times 10^{10}$  pbars/hour
- Stack at this rate for at least 15 hours
- Final Stack Parameters
  - Size =  $625 \times 10^{10}$  pbars
  - Transverse emittance  $< 15\pi$ -mm-mrad (95% normalized)
  - Longitudinal emittance  $< 50$  eV-Sec

## ■ Inputs

- Collect  $280 \times 10^6$  antiprotons from the target every 2 seconds
  - Transverse emittance =  $35\pi$ -mm-mrad (95% un-normalized)
  - Momentum Spread = 4%
  - Bunch lengths  $< 1.5$  nS

# Strategy

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- Present Run II Operations
  - Accumulator Core is the final repository for antiprotons
    - Bandwidth
    - Momentum aperture
    - Stacktail gain slope
  - 1/N effect in stochastic cooling limits stack size to  $\sim 300 \times 10^{10}$  pbars
- Run II Upgrades
  - The Recycler is the final repository for antiprotons
  - Electron cooling in the Recycler greatly reduces the 1/N effect
    - Larger average/peak stacking rate ratio
    - Larger stacks  $\sim 600 \times 10^{10}$
  - Accumulator Stacktail is optimized to handle larger flux by larger bandwidth and smaller gain slope
  - Greatly reduced Accumulator core size is also a result of larger bandwidth and smaller gain slope
  - Reduced Accumulator core size and high stacking rates require frequent and rapid transfers between the Accumulator and the Recycler

# Antiproton Stacking Process

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- Debuncher Bunch Rotation

- Exchange

- Large Momentum spread of 4% (360 MeV)
    - Short bunches < 1.5 nS (95%)

- For

- Small momentum spread of 0.4% (36 MeV)
    - Coasting beam

- Debuncher Cooling

- System Configuration

- Liquid Helium front end ( $T_{\text{eff}}=30\text{K}$ )
    - Bandwidth = 4-8 GHz Subdivided into 4 bands
    - Available kicker power
      - 2400 Watts/ plane (transverse)
      - 4800 Watts (momentum)

- Cooling Rate Specs.

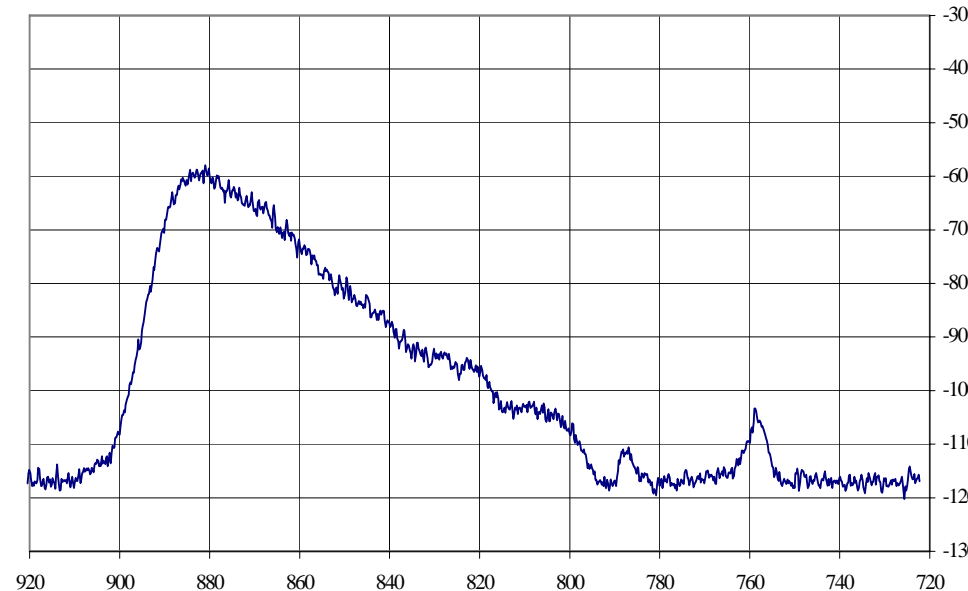
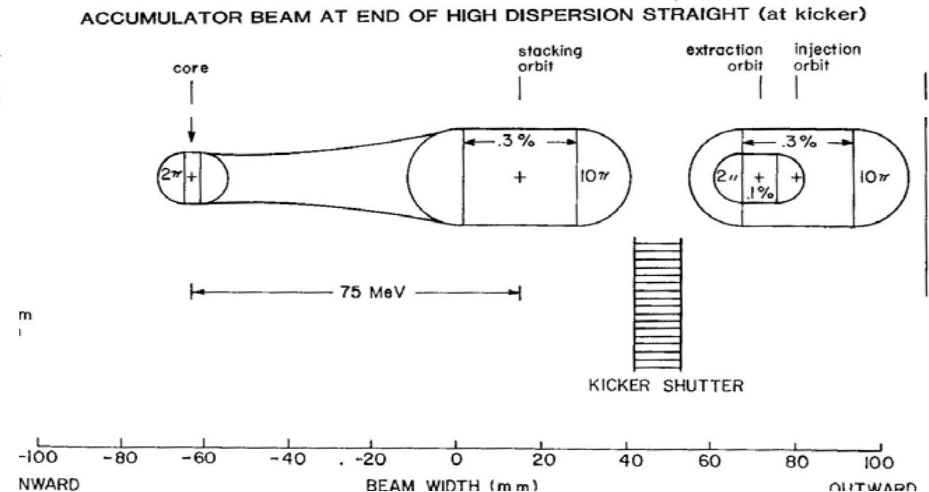
- Momentum: 36 MeV to 6 MeV in 1.9 Seconds
    - Transverse:  $35\pi$ -mm-mrad to  $5\pi$ -mm-mrad (95% un-normalized) in 1.9 seconds

# Antiproton Stacking Process

## ■ Accumulator Stacktail Cooling

### ➤ Process

- Beam is injected onto the Injection Orbit
- Beam is
  - Bunched with RF
  - Moved with RF to the Stacking Orbit
  - Debunched on Stacking orbit
- Stacktail pushes and compresses beam to the Core orbit
- Core Momentum system gathers beam from the Stacktail
- Accumulator Transverse Core Cooling system cools the beam transversely in the Stacktail and Core



# Antiproton Stacking Process

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- Accumulator Stacktail Cooling
  - Specifications
    - Injection pulse width: 6 MeV
    - Stacktail:
      - Bandwidth = 2-6 GHz
      - Width = 42 MeV
      - Gain slope = 8 MeV (can handle  $90 \times 10^{10}$  pbars/hr)
      - Power = 550W into 6400 $\Omega$
    - Core momentum
      - Bandwidth = 4-8 GHz
      - Aperture = 9.6 MeV
      - Gain slope = 5 MeV (can handle  $90 \times 10^{10}$  pbars/hr)
      - Stacksize =  $34 \times 10^{10}$  pbars
    - Extraction
      - Longitudinal emittance: 10eV-sec
      - Transverse emittance 1.0 $\pi$ -mm-mrad
      - Stacking interval: 30 minutes
      - Transfer size:  $22.5 \times 10^{10}$  pbars

# Antiproton Stacking Process

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## ■ Recycler Electron Cooling

- Every  $\frac{1}{2}$  hour an injected batch of  $22 \times 10^{10}$  pbars in 10 eV-Sec and  $1.0 \pi$ -mm-mrad phase space is injected into the Recycler
  - Transfers between the Accumulator and the Recycler
    - Are done on "event"
      - » ~instantaneously
      - » No more mini-shot setup
    - A 50% dilution is assumed to occur on each transfer
      - » 15 eV-Sec and  $1.5 \pi$ -mm-mrad phase space
  - Transverse stochastic pre-cooling of the injected batch
    - To bring the transverse emittance of the injected batch within the reach of the electron cooling
    - The injected batch is kept separate from the main "core" by barrier buckets
    - Transverse stochastic cooling systems are "gain gated"
      - » Low density injected batch - fast stochastic cooling
      - » High density core - slow stochastic cooling



# Antiproton Stacking Process

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## ■ Recycler Electron Cooling

- Every  $\frac{1}{2}$  hour, the previous injected batch is merged into the core with barrier bucket manipulations to make room for the new injected batch
- The Recycler Core
  - Is cooled mainly with electron cooling in all 3 planes
  - Weak transverse stochastic cooling for high amplitude particles
  - Intra-beam scattering (IBS) is "shut-off"
    - Recycler
      - » operates below transition
      - » has low dispersion
      - » has smooth lattice functions
    - The Core is squeezed with barrier buckets so that it occupies only 20% of the machine circumference
    - The transverse emittance is cooled to less than  $0.3\pi$ -mm-mrad (95% un-normalized) so that the beam temperature in all 3 planes is equal

# Antiproton Stacking and Cooling Projects

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- Accumulator Stacktail Upgrade
    - Project Leader: Paul Derwent
    - Major Objectives: Upgrade the Stacktail system to handle  $90 \times 10^{10}$  pbars/hour
      - Increase bandwidth of the system to 2-6 GHz
      - Reduce gain slope  $\sim 10$  MeV
  - Electron Cooling in the Recycler
    - Project Leader: Sergei Nagaitsev
    - Major Objectives: Install a 4.3 MV Pelletron in the Recycler
      - 500 mA of electron current
      - 20 meters of cooling section
  - Rapid Antiproton transfers from the Accumulator to the Recycler
    - Project Leader: Elvin Harms
    - Major Objectives: Transfer Accumulator core to the Recycler
      - in less than 1 minute every 30 minutes
      - $< 50\%$  emittance dilution
      - 95% transfer efficiency
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# Antiproton Stacking and Cooling Projects

WBS	Subproject	In Charge	Finish Date	M&S Est	M&S Cont
<b>1.3.3</b>	<b>Pbar Stacking and Cooling</b>	<b>Dave McGinnis</b>	<b>11/17/05</b>	<b>\$2,254,000.00</b>	<b>46%</b>
1.3.3.1	Stacking and Cooling Integration	Dave McGinnis	11/4/05	\$0.00	
1.3.3.2	Debuncher Cooling	Paul Derwent	6/2/03	\$0.00	
1.3.3.3	Stacktail Cooling	Paul Derwent	11/17/05	\$1,171,000.00	40%
1.3.3.3.1	Momentum	Paul Derwent	11/17/05	\$1,004,000.00	40%
1.3.3.3.2	Betatron	Paul Derwent	11/17/05	\$167,000.00	40%
1.3.3.4	Recycler Stacking and Cooling	Sergei Nagaitsev	4/8/05	\$0.00	
1.3.3.5	Electron Cooling	Sergei Nagaitsev	1/25/05	\$566,000.00	44%
1.3.3.5.1	Commission Full Beamline	Sergei Nagaitsev	3/19/04	\$55,000.00	45%
1.3.3.5.2	Design and procure components	Jerry Leibfritz/Sergei Na	1/30/04	\$373,000.00	42%
1.3.3.5.3	Disassemble Wideband Facility	Jerry Leibfritz/Sergei Na	6/1/04	\$22,000.00	58%
1.3.3.5.4	Transport Components to MI-31	Jerry Leibfritz	7/27/04	\$24,000.00	60%
1.3.3.5.5	Install Pelletron at MI-31	Jerry Leibfritz/Sergei Na	8/10/04	\$37,000.00	60%
1.3.3.5.6	Commission Pelletron	Sergei Nagaitsev	10/19/04	\$0.00	
1.3.3.5.7	Install E-Cool Transferline	Jerry Leibfritz	8/27/04	\$23,000.00	40%
1.3.3.5.8	Modifications to MI/RR	Jerry Leibfritz	9/18/03	\$15,000.00	40%
1.3.3.5.9	Install Cooling Section in RR	Jerry Leibfritz/Sergei Na	9/6/04	\$17,000.00	40%
1.3.3.5.10	Commission Cooling Section	Sergei Nagaitsev	9/23/04	\$0.00	
1.3.3.5.11	Commission Electron Cooling	Sergei Nagaitsev	1/25/05	\$0.00	
1.3.3.6	Rapid Transfers	E Harms	5/5/05	\$517,000.00	60%
1.3.3.6.1	Document Fast Transfer scheme	E Harms	4/21/03	\$0.00	
1.3.3.6.2	Beam Line Regulation	E Harms	2/13/04	\$12,000.00	40%
1.3.3.6.3	RT Software	E Harms	3/4/05	\$0.00	
1.3.3.6.4	Oscillation Feedback and Control	B Foster	1/9/04	\$0.00	
1.3.3.6.5	Diagnostics	E Harms	12/16/04	\$505,000.00	60%
1.3.3.6.6	Commission Fast Transfers	E Harms	5/5/05	\$0.00	

# Accumulator Stacktail Upgrade Project Strategy

- Design margin for flux =  $90 \times 10^{10}$  pbars/hour

$$\Phi_o = \frac{|\eta| W^2 E_d}{f_o \beta_{pc} \ln\left(\frac{f_{\max}}{f_{\min}}\right)}$$

- The best way to increase flux is to increase the bandwidth
- Large  $E_d$  needs a large momentum aperture or results in a low final core density
- Energy Aperture and Stability
  - Would like energy aperture as big as possible to get a large core density
  - For system stability, operate at frequencies where Schottky bands do not overlap
  - Strategies

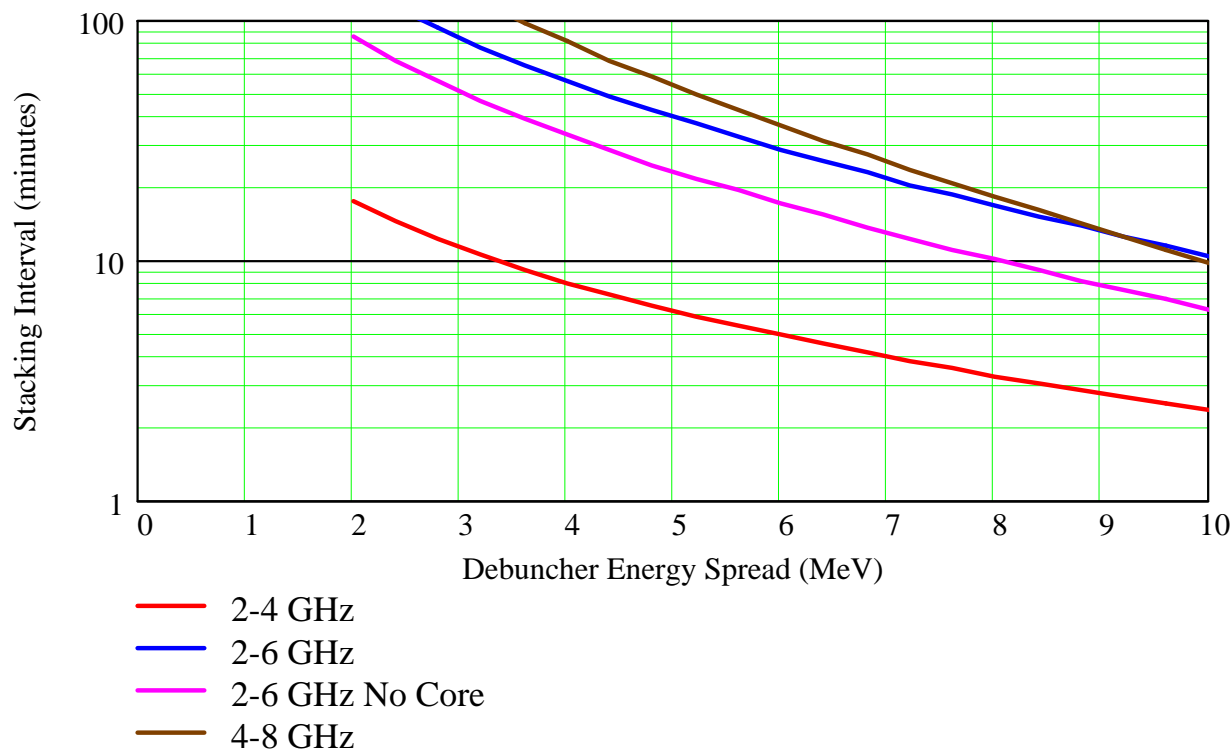
s aperture  
 ng heating  
 ing system  
 bandwidth  
 pickup and kicker at high frequencies  
 frequencies

# Accumulator Stacktail Upgrade Project Strategy

## Core Density and Stacking Interval

- Particles to be transferred must be inside desired Recycler longitudinal emittance
- Desire long stacking interval
  - Small Debuncher energy spread  $\Delta E_{bd}$
  - Large energy aperture  $\Delta E_s + \Delta E_c$
  - Small characteristic energy slope ( $E_d$ )

Stacktail Bandwidth (GHz)	Core Bandwidth (GHz)	$E_{ds}$ (MeV)	$E_{dc}$ (MeV)	$\Delta E_s + \Delta E_{bd}$ (MeV)	$\Delta E_c$ (MeV)	Fraction Unstacked (%)
2-4	4-8	20	5	77.4	9.6	50
2-6	4-8	8	5	48.4	9.6	66
2-6	2-6	8	8	45.2	12.8	55
4-8	4-8	5	5	33.9	9.6	72



# Recycler Electron Cooling Project Strategy

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- Decide on whether to do longitudinal cooling and/or betatron cooling
  - Longitudinal cooling rate independent of  $\beta$  function
    - Important for the Recycler
  - Transverse cooling rate proportional to  $\beta^{1/2}$ 
    - Not as important for the Recycler
- Design for minimum angular spread in electron beam
  - Cooling section solenoid field quality
  - Aberrations in the beamline
  - Stability of the antiproton orbit
  - Stability of the electron optics
  - Emittance and space charge
  - Stray magnetic fields
- Decide on reasonable emittance range for optimum cooling

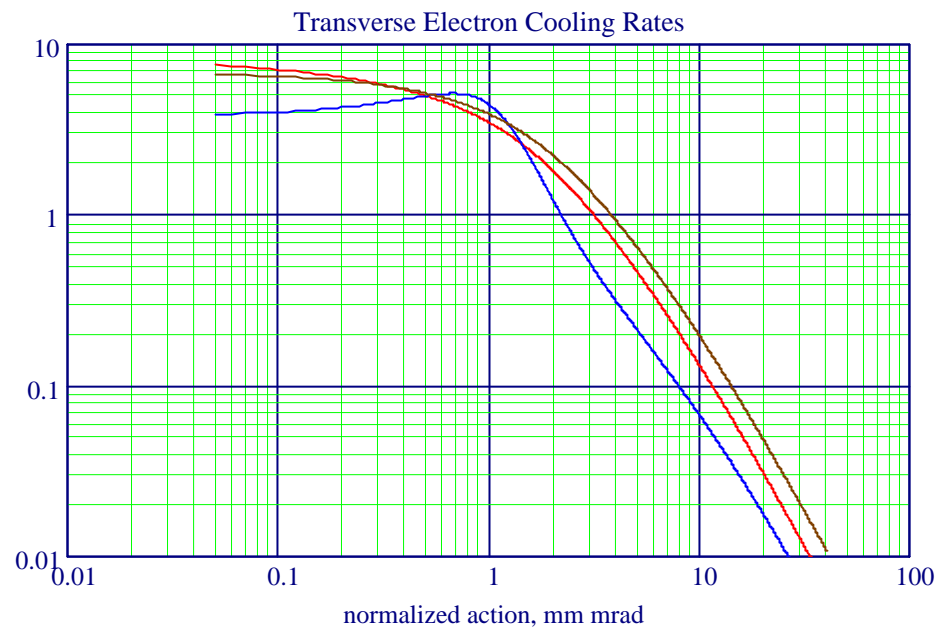
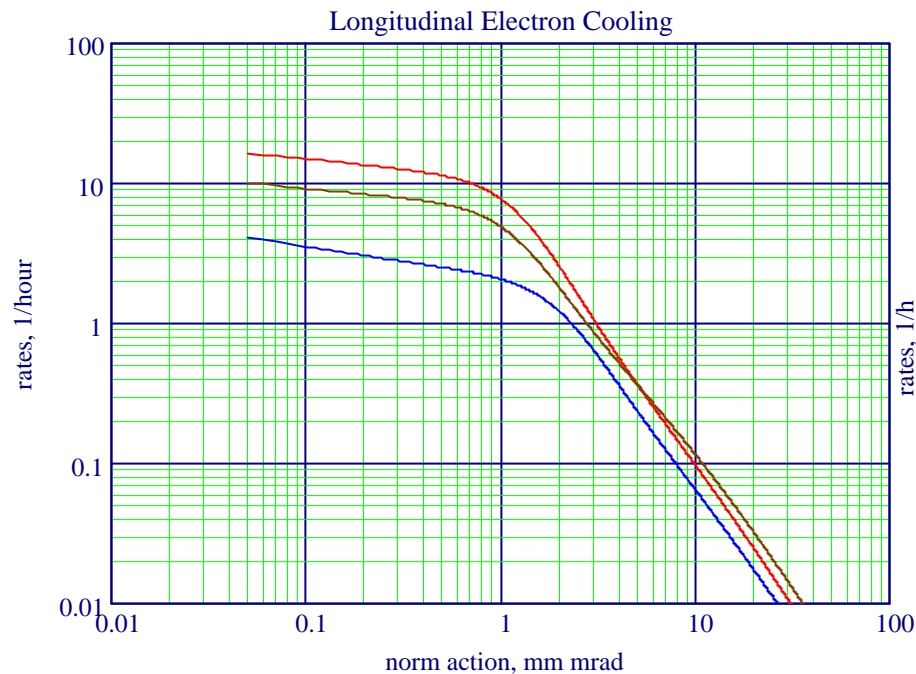
$$\sqrt{\frac{\epsilon_{95\%}}{6\beta}} \approx \Delta\theta_{\text{electron spread}}$$

$$r^2 = \epsilon_{95\%} \beta$$

- Design electron beam size

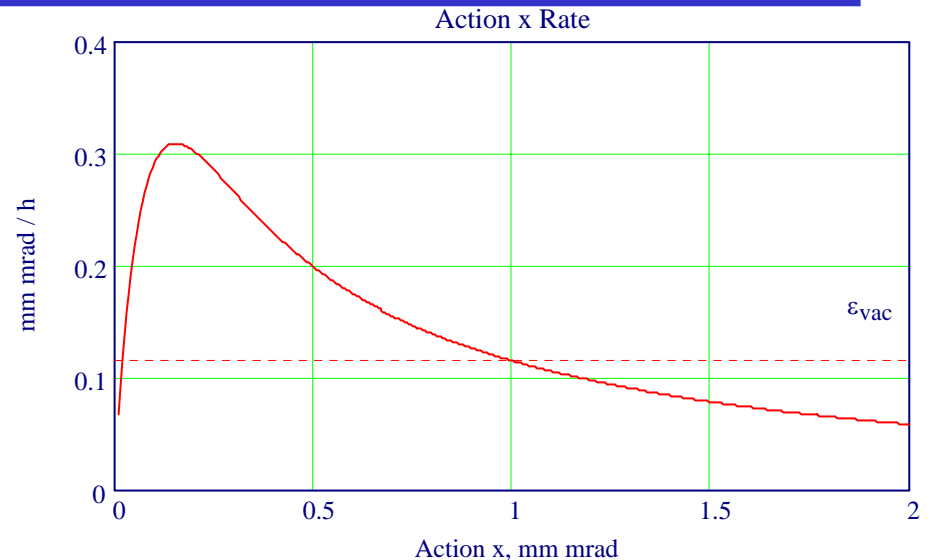
# Recycler Electron Cooling Project Strategy

- Emphasis on longitudinal cooling
- Electron Beam Current = 500 mA
- Angular spread of electron beam = 0.22 mrad
- Design cooling for transverse emittance of  $3\pi$ -mm-mrad (normalized) with Electron beam size = 3 mm with  $\beta=22\text{m}$
- Longitudinal Cooling time needed = 25 minutes

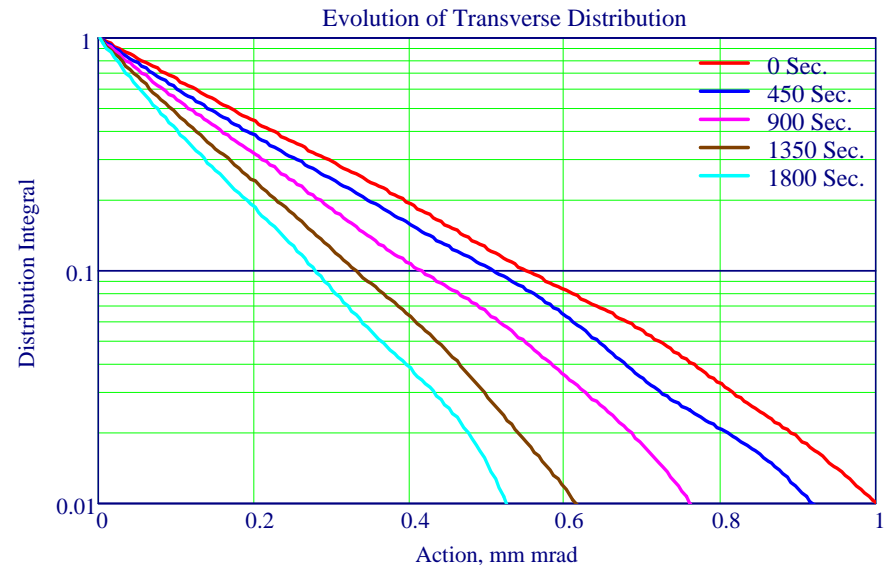


# Recycler Stochastic Pre-cooling and Vacuum

- Needed to transversely pre-cool  $22 \times 10^{10}$  pbars injected from the Accumulator for  $\frac{1}{2}$  hour to bring the transverse emittance within reach of the electron cooling



- Evolution of the injected batch with  $22 \times 10^{10}$  pbars using a Q=1 2-4 GHz Transverse Stochastic Cooling system,  $0.7\pi$ -mm-mrad/hr vacuum growth rate





# Rapid Transfers Project Strategy

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- Transfers are done on event
  - Halt to stacking
  - Accumulator RF Extraction
  - Transfer to the Recycler
  - Recycler Barrier Bucket manipulation
  - Return to stacking
- P1, P2, and AP1 power supplies ramp on every event
  - No more bi-modal operation of AP1
- Fast Feedback
  - Random oscillations are corrected by injection dampers in the Main Injector and Recycler
    - 1 kV in ~80 turns will damp  $2\pi$ -mm-mrad (95% normalized) oscillation
  - 8 GeV transfer line magnet power supplies regulation specification to  $2\pi$ -mm-mrad
- Slow Feed-Forward
  - Transfer line reference orbit
    - Transfer line BPM system
  - Injection oscillations
    - Turn-by-turn info provided by damper systems.

# Key Parameters

Parameter	Value	Unit
Average Stacking rate	40	$\times 10^{10}$ per hour
Peak Stacking rate	45	$\times 10^{10}$ per hour
Number of particles injected into the Debuncher	280	$\times 10^6$
Debuncher transverse aperture	35	$\pi$ -mm-mrad
Antiproton production cycle time	2	Secs
Maximum bunch length on target	1.5	nSecs.
Debuncher momentum aperture	4	%
Debuncher momentum cooling aperture	0.4	%
Debuncher final transverse emittance	5	$\pi$ -mm-mrad
Debuncher final momentum spread	6	MeV
Debuncher transverse cooling common mode rejection	1.5	mm
Debuncher transverse cooling phase imbalance	3	degrees
Debuncher transverse cooling delay imbalance	1.4	pS
Debuncher momentum notch filter delay tolerance	1	pS
Debuncher momentum cooling notch filter dispersion	2.5	degrees
Debuncher to Accumulator transfer efficiency	95	%
Accumulator Stacktail Momentum bandwidth	2-6	GHz
Accumulator Core Momentum bandwidth	4-8	GHz
Accumulator Stacktail Momentum energy slope	8	MeV
Accumulator Stacktail Power	625	Watts
Accumulator Stacktail 2-6 GHz kicker impedance	6400	$\Omega$
Accumulator Core Momentum energy slope	5	Mev
Accumulator Core Momentum cooling aperture	9.6	MeV
Accumulator Momentum cooling aperture	58	MeV

# Key Parameters

Parameter	Value	Unit
Accumulator Momentum cooling aperture	58	MeV
Accumulator to Recycler transfer longitudinal emittance	10	eV-Sec
Accumulator to Recycler transfer interval	30	minutes
Number of particles extracted from the Accumulator per transfer	24	$\times 10^{10}$
Accumulator to Recycler transfer time	1	minutes
Accumulator to Recycler transfer efficiency	95	%
Accumulator core transverse emittance	1	$\pi$ -mm-mrad
Recycler transverse emittance injection dilution	50	%
Recycler longitudinal emittance injection dilution	50	%
Recycler transverse Stochastic Cooling Bandwidth	>1	GHz
Recycler Transverse Stochastic cooling Center Frequency	3	GHz
Maximum Recycler Transverse emittance Growth Rate	0.7	$\pi$ -mm-mrad/hr
Peak Stack in Recycler	620	$\times 10^{10}$
Transverse emittance of antiprotons extracted from Recycler	1	$\pi$ -mm-mrad
Total Longitudinal emittance of antiprotons extracted from Recycler	50	eV-Sec
Number of bunches extracted from the Recycler	36	
Minimum longitudinal cooling rate of Electron Cooling	55	eV-Sec/hour
Minimum Electron Cooling Current	250	mA
Electron Beam alignment tolerance	0.1	mrad
Transverse electron cooling rate per 100 mA	0.12	$\pi$ -mm-mrad
Maximum transverse emittance for electron cooling	1.5	$\pi$ -mm-mrad

# Key Parameter Comparison

Parameter	Value FY06	Value FY04	Value Now	Unit
Average Stacking rate	40	12	8.5	$\times 10^{10}$ per hour
Peak Stacking rate	45	18	13	$\times 10^{10}$ per hour
Beam on Target	8	5	4.7	$\times 10^{12}$
Number of particles injected into the Debuncher	280	100	90	$\times 10^6$
Debuncher transverse aperture	35	15	15	$\pi$ -mm-mrad
Antiproton production cycle time	2	1.7	2.2	Secs
Maximum bunch length on target	1.5	1.3	1.3	nSecs.
Debuncher momentum aperture	4	3.7	3.7	%
Debuncher momentum cooling aperture	0.4	0.4	0.4	%
Debuncher final transverse emittance	5	5	5	$\pi$ -mm-mrad
Debuncher final momentum spread	6	5	9	MeV
Debuncher transverse cooling common mode rejection	1.5	1	<1	mm
Debuncher transverse cooling phase imbalance	3	20	30	degrees
Debuncher transverse cooling delay imbalance	1.4	10	14	pS
Debuncher momentum notch filter delay tolerance	1	1	2-3	pS
Debuncher momentum cooling notch filter dispersion	8	10	20	degrees
Debuncher to Accumulator transfer efficiency	95	95	95	%
Accumulator Stacktail Momentum bandwidth	2-6	1.7-3.7	1.7-3.7	GHz

# Key Parameter Comparison

Parameter	Value FY06	Value FY04	Value Now	Unit
Accumulator Core Momentum bandwidth	4-8	4-7	2-4	GHz
Accumulator Stacktail Momentum energy slope	8	11	11	MeV
Accumulator Stacktail Power	625	280	250	Watts
Accumulator Stacktail 2-6 GHz kicker impedance	6400	6400	6400	$\Omega$
Accumulator Core Momentum energy slope	5	6	11	Mev
Accumulator Core Momentum cooling aperture	9.6	12	20	MeV
Accumulator Momentum cooling aperture	58	72	80	MeV
Accumulator to Recycler transfer longitudinal emittance	10	15	15	eV-Sec
Accumulator to Recycler transfer interval	30	180	180	minutes
Number of particles extracted from the Accumulator per transfer	24	24	25	$\times 10^{10}$
Accumulator to Recycler transfer time	1	15	60	minutes
Accumulator to Recycler transfer efficiency	95	90	70	%
Accumulator core transverse emittance	1	1	1	$\pi$ -mm-mrad
Recycler transverse emittance injection dilution	50	50	>100	%
Recycler longitudinal emittance injection dilution	50	50	>100	%
Peak Stack in Recycler	620	200	80	$\times 10^{10}$
Transverse emittance of antiprotons	1	1	-	$\pi$ -mm-mrad
Total Longitudinal emittance of antiprotons	50	50	100	eV-Sec
Transverse stochastic cooling time @ 100e10	0.7	0.7	-	hours

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1.3.3.6.2	Beam Line Regulation	E Harms	2/13/04	\$12,000.00	40%
1.3.3.6.3	RT Software	E Harms	3/4/05	\$0.00	
1.3.3.6.4	Oscillation Feedback and Control	B Foster	1/9/04	\$0.00	
1.3.3.6.5	Diagnostics	E Harms	12/16/04	\$505,000.00	60%
1.3.3.6.6	Commission Fast Transfers	E Harms	5/5/05	\$0.00	

# Antiproton Stacking and Cooling Milestones

WBS	Subproject/Milestone	MS Class	MS Date
<b>1.3.3</b>	<b>Pbar Stacking and Cooling</b>		
<b>1.3.3.3</b>	<b>Stacktail Cooling</b>		
1.3.3.3.1	Momentum		
1.3.3.3.1.1.5	Review System Design: stacktail momentum (Milestone)	C	1/5/04
1.3.3.3.1.2.4	Stacktail Reconfigured (option) (Milestone)	C	8/10/04
1.3.3.3.1.9	Acc Momentum Operational (Milestone)	A	11/17/05
1.3.3.3.2	Betatron		
1.3.3.3.2.1.2	Review System Design: stacktail betatron (Milestone)	C	11/28/03
1.3.3.3.2.8	Acc Betatron Operational (Milestone)	A	11/17/05
<b>1.3.3.4</b>	<b>Recycler Stacking and Cooling</b>		
1.3.3.4.2	Commissioning Parameters Defined (Milestone)	C	5/30/03
1.3.3.4.4	Commissioning Plan Evaluation (Milestone)	B	11/14/03
1.3.3.4.5	RR Commissioned for Electron Cooling (Milestone)	A	7/2/04
<b>1.3.3.5</b>	<b>Electron Cooling</b>		
1.3.3.5.1	Commission Full Beamline		
1.3.3.5.1.11	Demonstrate beam properties at Wide Band Lab (Milestone)	B	3/19/04
1.3.3.5.2	Design and procure components		
1.3.3.5.2.1	Pelletron extension parts received (Milestone)	C	1/1/04
1.3.3.5.6	Commission Pelletron		
1.3.3.5.6.1	Pelletron Installed at MI-31 (Milestone)	C	8/11/04
1.3.3.5.12	Electron Cooling Operational (Milestone)	A	1/25/05
<b>1.3.3.6</b>	<b>Rapid Transfers</b>		
1.3.3.6.7	Rapid Transfers Operational (Milestone)	A	5/5/05
<b>1.3.6.2</b>	<b>Project Milestones</b>		
1.3.6.2.2	Review: RR and Electron Cooling Commissioning Plan (Milestone)	A	12/16/03
1.3.6.2.3	Review: Phase 2-4 Transition Plan (Milestone)	A	4/16/04

# Drivers

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## ■ Cost

- Accumulator Stacktail Upgrade
  - Travelling Wave Tubes
- Electron Cooling
  - 5 MV Pelletron (already purchased)
  - MI31 Civil construction (already underway)
  - Transfer line components
- Rapid Transfers
  - Transfer lines 53 MHz BPM Upgrade

## ■ Schedule

- Accumulator Stacktail Upgrade
  - Procurement of the Traveling Wave Tubes
- Electron cooling
  - Recycler commissioned for Electron Cooling
  - Electron beam properties measured at Wideband
  - Electron cooling installed at MI31